

# SIGNAL DELAY STABILITY OF A KU-BAND TWO-WAY SATELLITE TIME TRANSFER TERMINAL

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## Abstract

*A fully automated two-way time and frequency transfer (TWSTFT) system including a satellite simulator, which allows to carry out signal delay measurements in conjunction with each time transfer measurement, is operated at the Technical University Graz (TUG). After a brief description of the system, results obtained during fifteen months of operation are presented and discussed. Finally envisaged experiments are mentioned.*

## INTRODUCTION

The signal delay stability of the receiving equipment (one-way methods) and of the receiving and transmit equipment (two-way methods) is a crucial parameter for the performance of time and frequency transfer systems. Apart from the use of transfer standards to assess the differential signal delay of stations, the use of local means to monitor signal delay variations – allowing frequent measurements – is of great interest. For satellite time transfer stations, this can be accomplished by using a satellite simulator attached to the antenna of the station. Such a system has been operated for longer than a year together with the two-way satellite time and frequency transfer (TWSTFT) station of the Technical University Graz (TUG), enabling the individual measurement of the difference of the transmit and receive delays for each time transfer session in a completely automated procedure<sup>[1]</sup>.

The correction which has to be applied to TWSTFT measurements is given by  $[(\tau_1^{TX} - \tau_1^{RX}) - (\tau_2^{TX} - \tau_2^{RX})]^{1/2}$ , i.e. the difference of the differential delays of the transmit and receive parts of earth stations 1 and 2 divided by two<sup>[2]</sup>. The transmit delay is the total delay from the transmitted one pulse per second (1 PPS) to the reference plane of the antenna and the receive delay is the total delay of the received 1 PPS. Both delays consist of the corresponding signal delays of the earth station, the modem, related equipment, and in the connecting cables. The employed satellite simulator (SATSIM) allows to measure most of these delays except some

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remaining delays which have to be evaluated separately. The signal delays are measured by means of the spread-spectrum modem used for the time and frequency transfer measurements. The separate transmit and receive delays of a single modem can be measured by means of an oscilloscope, but only with low accuracy. With two modems the corresponding differential delays can be established with high accuracy.

## MEASUREMENT SETUP

A detailed description of the TWSTFT system used at TUG is given in [1]. The SATSIM used is of the de Jong type<sup>3, 4)</sup> — this means one can measure the sum of the earth station transmit and receive delays as well as the receive delay only, thus allowing one to calculate the difference of the transmit and receive delay — but shows some modifications. The receive and transmit antennas are not simply waveguide-to-coax transitions, but are horn antennas and, in the receive part, there is a power splitter, making possible to measure power and frequency of the signal transmitted by the earth station. In the transmit part, a combination of attenuators is used to obtain the same signal power as received from the satellite. For shielding purposes all components are in a small metallic box with the horn antennas protruding from the box. The box is mounted on the feed boom of the parabolic antenna with the horns facing the feed. The side of the box with the horns is covered with microwave absorbing material and protection from rain is achieved by a small dome. The station is fully automated, providing remote control of transmit power, of transmit and receive frequencies, and of a spectrum analyzer for various measurement and monitoring purposes. Apart from the actual time transfer measurements, a time-transfer session consists of several accompanying measurements: collection of meteorological data, a counter check, the modem calibration, carrier-to-noise power density ratio ( $C/N_0$ ) measurements of the satellite beacon and of the carriers of the local and remote station, and the different loop measurements necessary for the calculation of the signal delays of the station.

A block diagram of the station from the point of view of the signal delays involved and the possible loop arrangements to measure the signal delays of interest is shown in Figure 1. The different loops and the corresponding counter readings ( $REF - PPSRX + b2$ ) are called: MOD for modem loop, ID for indoor loop (all indoor equipment is in a fully air-conditioned room), OD for outdoor loop, STR for SATSIM loop to measure the station transmit and receive delay, and SR for SATSIM loop to measure the station receive delay. Together with the wanted delays other delays are measured which can only partly be eliminated by combining different measurements. These remaining delays have to be evaluated separately. CAL is the modem calibration ( $REF - PPSTX + b1$ ) by which TWSTFT measurements have to be corrected to take into account the delay between the time reference REF and the transmitted 1 PPS PPSTX. Each delay indicated in a square gives the signal delay between the points marked by dots, e.g.  $u1$  is the signal delay from the modem output to the indoor switch input and so on. In order to distinguish between the transmit and receive delays mentioned above and indicated by  $\tau$ , the measured delays are indicated by  $t$ . The transmit delay  $t^{TX}$  (modem transmit output to satellite simulator input not including the cable connecting indoor and outdoor equipment) given by  $(u1 + i1 + o1 + u3 + u4)$  is obtained by calculating  $(STR - SR)$  and applying the correction  $[c1 + c2 + (s2 - s1) + (cc - uc)]$ . The receive delay  $t^{RX}$  (satellite simulator output

to modem receive input not including the cable connecting outdoor and indoor equipment) given by  $(d4 + d3 + o2 + i2 + d1)$  is obtained by calculating  $(SR - MOD - OD + ID)$  and applying the correction  $[-(c1 + c2) - s2 - (cc - uc) - (m1 + m2 - m3) - (i3 - o3 - i1 - i2)]$ . The differential delay  $(t^{TX} - t^{RX})/2$  is obtained by calculating  $(STR - 2*SR + MOD + OD - ID)/2$  and applying the correction  $[(c1 + c2) + (s2 - s1/2) + (cc - uc) + (m1 + m2 - m3)/2 + (i3 - o3 - i1 - i2)/2]$ . Apart from  $(c1 + c2)$  all other terms can either be assumed to be zero or smaller than 1 ns. The delay  $c1$  is 14.55 ns and  $c2$  is about 20 ns. The cables connecting the indoor and outdoor equipment (delays:  $cc$ ,  $uc$ ,  $dc$ ) are parts of equal lengths (approx. 30 m) of one cable and in the same duct. Therefore, signal delay variations are assumed to be equal for all of them. The sum of  $uc$  and  $dc$  and related delays  $(OD - ID)$  is measured for each session and the three individual delays ( $cc$ ,  $uc$ ,  $dc$ ) are measured occasionally like other delays which in the present setup cannot be measured in an automated mode. In the following the respective delays  $t$  are given without the above mentioned corrections and are designated by  $T$ .

## MEASUREMENTS AND RESULTS

TWSTFT measurements are carried out between two laboratories in the USA and six laboratories in Europe<sup>15, 61</sup>. Since summer 1994 in connection with each session all loop measurements necessary to calculate the differential delay are performed. Each single loop measurement is the mean of 100 measurements with one measurement per second. The completion of all loop measurements takes about fifteen minutes, but could be shortened to about 10 minutes. The measurement error estimated by an error budget taking into account the errors contributed by the single measurements is smaller than 50 ps.

In the following, measurements accompanying the European sessions are presented. The differential delay  $(T^{TX} - T^{RX})/2$  — computed from the delays as measured — and the outside temperature are given in Figures 2 and 3. There is an obvious correlation between the differential signal delay of the station and the outside temperature. Figure 4 shows the differential delay computed from the transmit and receive delays corrected for their modeled temperature and humidity behavior. For the modeling of the temperature and humidity dependence of the transmit and receive delays, polynomial fits were used. During the reported period of about fifteen months a total variation of the temperature of about 35°C and a total variation of the uncorrected differential delay of about 1.5 ns can be observed. The uncorrected data show a trend with a superimposed seasonal variation of about 600 ps. This trend still exists for the data with the modeled temperature and humidity dependence removed and seems to represent a kind of aging effect resulting in a delay increase of about 400 ps.

## DISCUSSION OF RESULTS

The stability<sup>[7]</sup> of the differential delay  $(T^{TX} - T^{RX})$  as measured and of the corrected one, together with stabilities typically obtained for TWSTFT measurements for averaging times up to 100 s and with stabilities of crucial system elements, is given in Figure 5. This is a composite time and frequency stability plot; thus, from only one graph the time and frequency transfer capability of a system can be estimated<sup>[11]</sup>. Stabilities were calculated from long-term sessions

performing one measurement per second or from measurements carried out three times per week (Monday, Wednesday, Friday) during the regular TWSTFT sessions also performing one measurement per second. The results obtained from the latter ones were interpolated to one-day intervals to obtain equally spaced data for the stability calculation, but no corrections to the obtained stabilities were applied<sup>[8]</sup>. The measurements of the differential delay show flicker noise PM with a level around 100 ps. This is in agreement with results obtained for TWSTFT common-clock experiments<sup>[9]</sup>. For averaging times up to some minutes TWSTFT usually shows white-noise PM behavior as indicated in Figure 5, with the noise level depending on the actual  $C/N_0$  of the signal supplied to the modem. The ultimate limit in the currently used TWSTFT measurement scheme is given by the stability of the electronic counter used for the time interval measurements. A more critical limit seems to result from phase variations between the reference frequency used by the modem for the signal generation and the time reference to which the measurements are referred. These phase variations are reflected in CAL, the modem calibration ( $REF - PPSTX + b1$ ). Stabilities of CAL for the initially used frequency distribution system and an upgraded system are also given in Figure 5. Because CAL is not measured every second during a TWSTFT session, but a mean value of 100 measurements performed before or after a session is used, the short-term stability of CAL is crucial for the short-term stability of TWSTFT measurements.

## CONCLUSION AND ENVISAGED ACTIVITIES

Performing TWSTFT measurements between stations both equipped with a SATSIM and correcting the TWSTFT data of each station by the measured signal delay variations could considerably improve the TWSTFT stability. In a measurement setup designed for fully automated measurements, a SATSIM can easily be included and operated. Because during the SATSIM operation the earth station is transmitting, about five minutes of extra satellite time is needed. The data obtained can immediately be used to correct the TWSTFT data for possible variations of the differential signal delay of the station. At the TUG a second earth station will soon be available, allowing common clock experiments between two stations both equipped with a SATSIM and, thus, the obtaining of some more information on the stability limits of TWSTFT systems. Furthermore, the second station will be used for detailed investigations concerning temperature and humidity dependence of the signal delays in order to optimize the station design.

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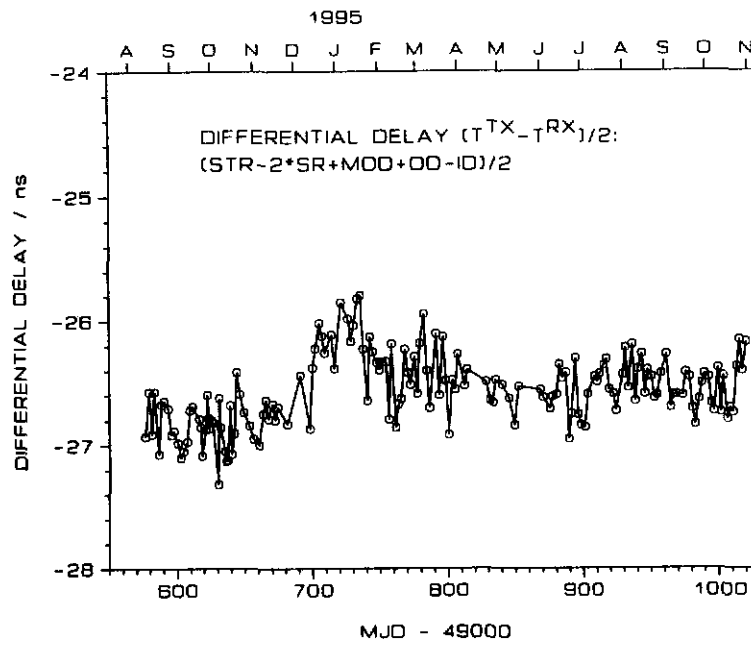


Figure 2 Differential delay  $(T^{TX} - T^{RX})/2$  computed from  $T^{TX}$  and  $T^{RX}$  as measured.

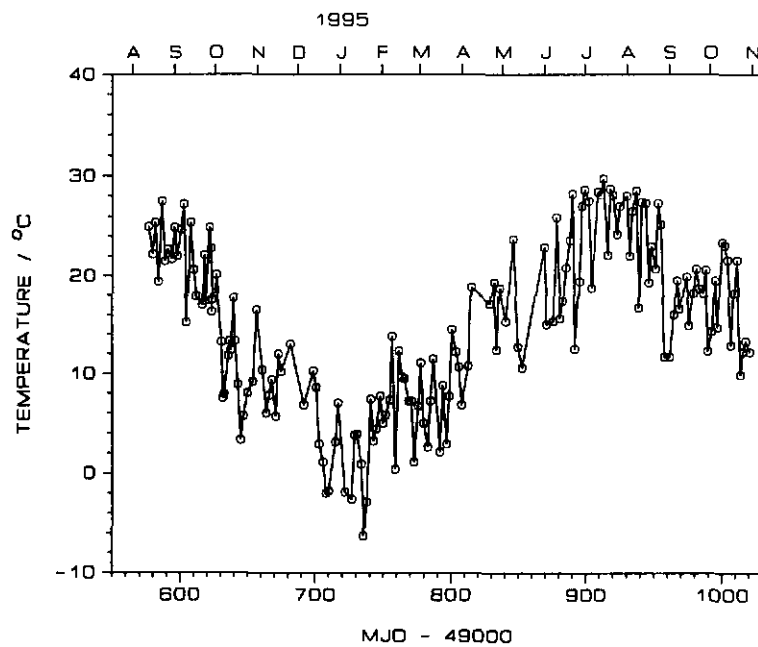


Figure 3 Outside temperature.



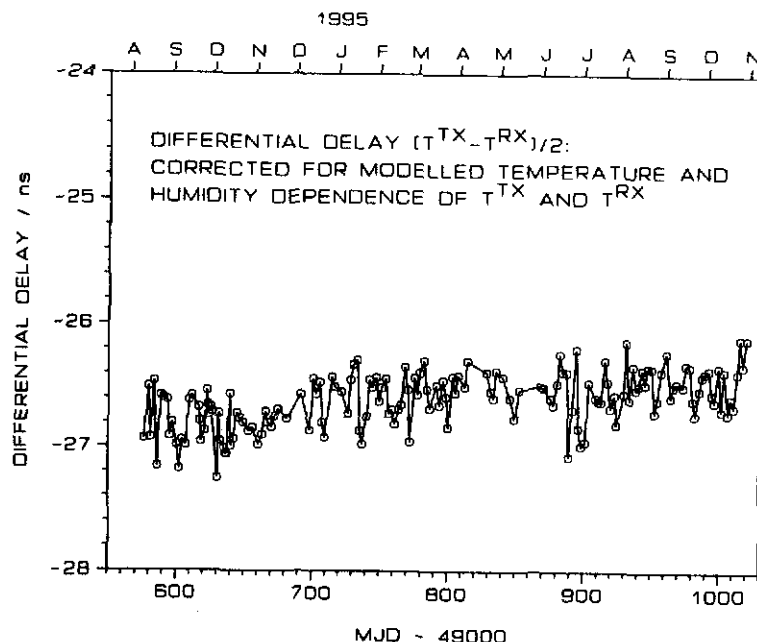


Figure 4 Differential delay  $(T^{TX} - T^{RX})/2$  computed from  $T^{TX}$  and  $T^{RX}$  corrected for modelled temperature and humidity dependence of  $T^{TX}$  and  $T^{RX}$

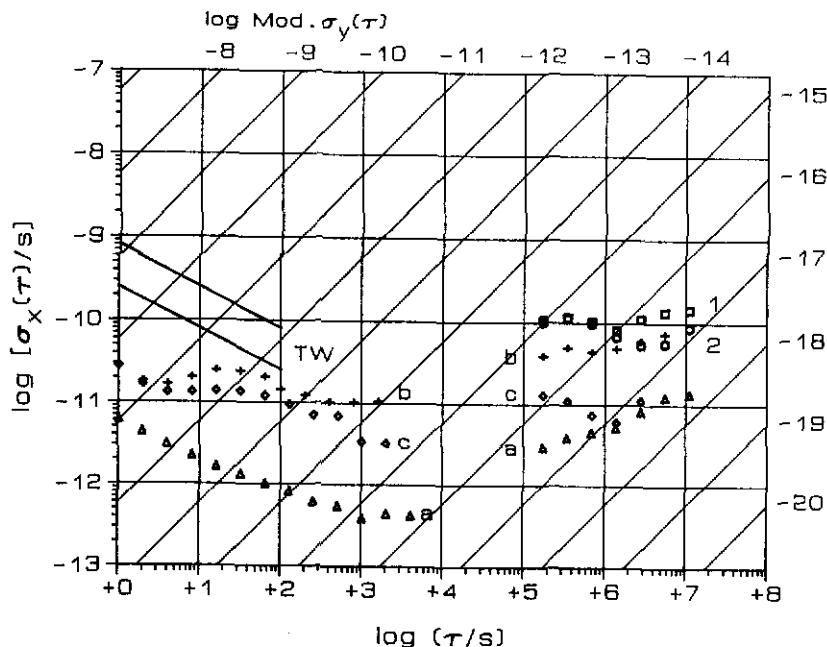


Figure 5 Stabilities of differential delays  $(T^{TX} - T^{RX})/2$  as measured (1) and corrected for temperature and humidity (2), of TWSTFT measurements (TW), of an electronic counter used for TWSTFT measurements (a), and of the modem calibration CAL for the initially used (b) and an upgraded (c) frequency and time distribution system.

## Questions and Answers

**DR. GERNOT WINKLER (USNO, RETIRED):** If you provide a correction, depending on temperature and humidity, you have to consider that humidity and temperature are strong correlators.

**DIETER KIRCHNER (TECHNICAL UNIVERSITY GRAZ):** Yes, I know.

**DR. GERNOT WINKLER (USNO, RETIRED):** It's better to use temperature and absolute water content, because that is the physical parameter which is independent of temperature – less correlated with temperature. So using absolute humidity, or grams per cubic meter water content, and temperature should give you a better result.

**DIETER KIRCHNER (TECHNICAL UNIVERSITY GRAZ):** Thank you for this comment, Dr. Winkler. But again, for the real operation, we will simply use the measured figures. Maybe I have to add an error budget is an error smaller than 50 picoseconds for one calibration measurement.